



(12) **United States Patent**  
**Kaminski**

(10) **Patent No.:** **US 9,058,909 B2**  
(45) **Date of Patent:** **\*Jun. 16, 2015**

(54) **BEAM FORMING APPARATUS**

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(71) Applicant: **Rapiscan Systems, Inc.**, Torrance, CA (US)

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(72) Inventor: **Joseph W. Kaminski**, Campbell, CA (US)

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(73) Assignee: **Rapiscan Systems, Inc.**, Torrance, CA (US)

(\*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

This patent is subject to a terminal disclaimer.

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Primary Examiner — Courtney Thomas

(74) Attorney, Agent, or Firm — Novel IP

(65) **Prior Publication Data**

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(51) **Int. Cl.**  
**G21K 1/04** (2006.01)

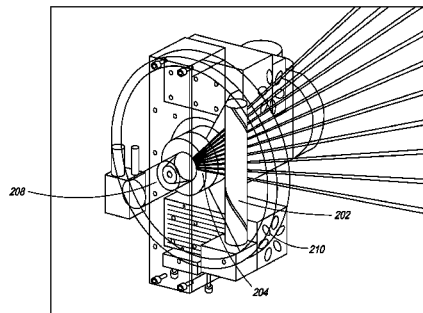
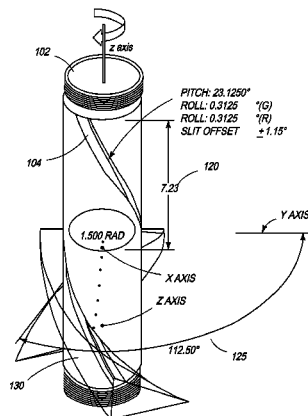
(52) **U.S. Cl.**  
CPC ..... **G21K 1/043** (2013.01); **G21K 1/046** (2013.01)

(58) **Field of Classification Search**  
CPC ..... G21K 1/04; G21K 1/043; A61B 6/06  
USPC ..... 378/160  
See application file for complete search history.

(57) **ABSTRACT**

The present specification discloses a beam chopping apparatus, and more specifically, a helical shutter for an electron beam system that is employed in radiation-based scanning systems, and more specifically, a beam chopping apparatus that allows for variability in both velocity and beam spot size by modifying the physical characteristics or geometry of the beam chopper apparatus. The present specification also discloses a beam chopping apparatus which provides a vertically moving beam spot with substantially constant size and velocity to allow for substantially equal illumination of the target. In addition, the present specification is a beam chopping apparatus that is lightweight and does not cause an X-ray source assembly employing the beam chopper to become heavy and difficult to deploy.

**19 Claims, 18 Drawing Sheets**



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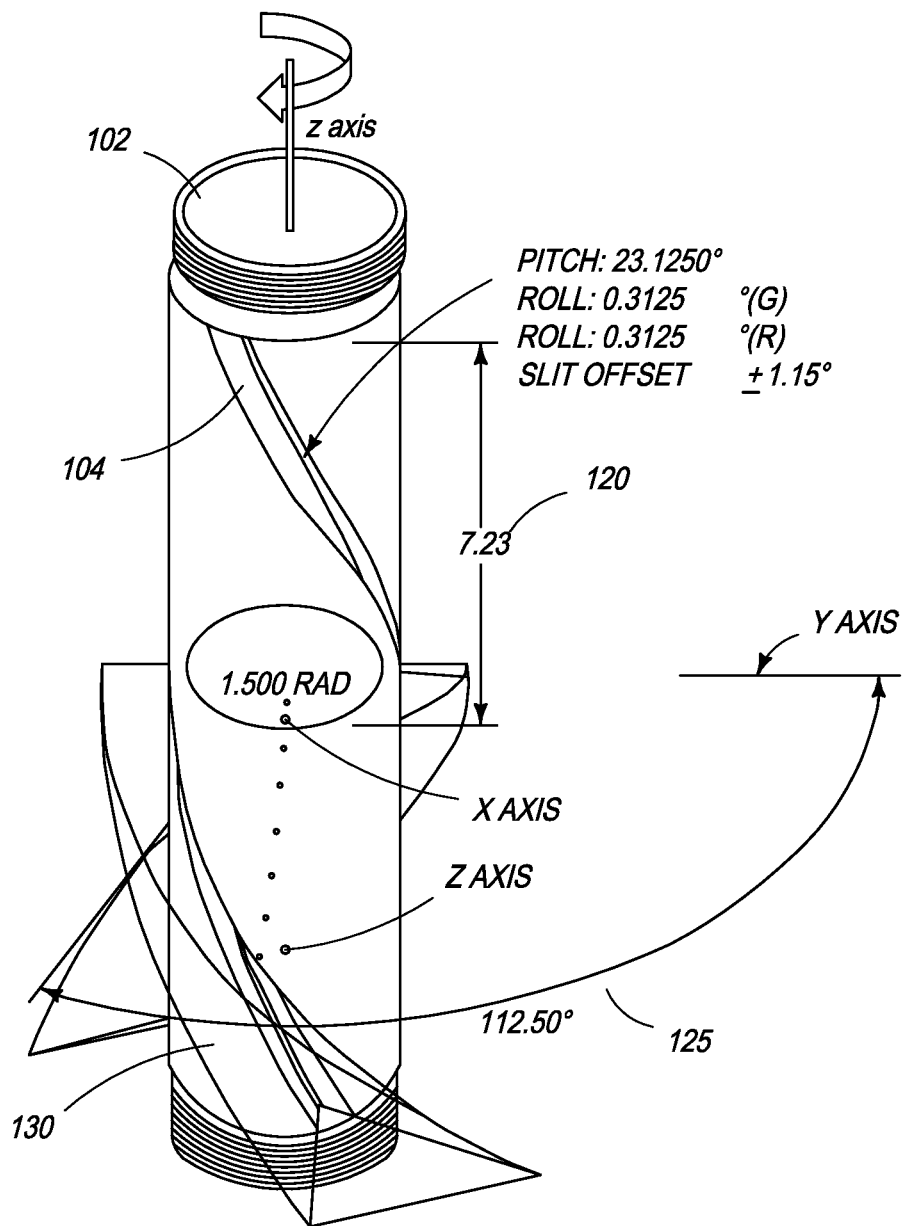


FIG. 1

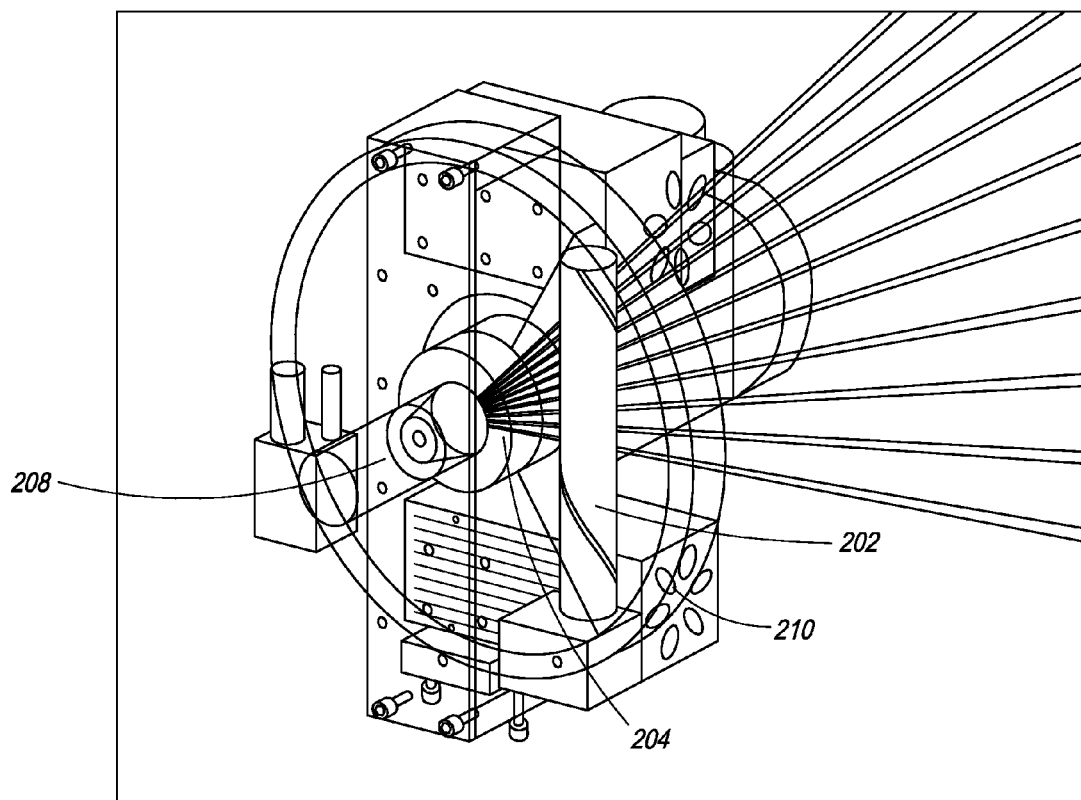


FIG. 2

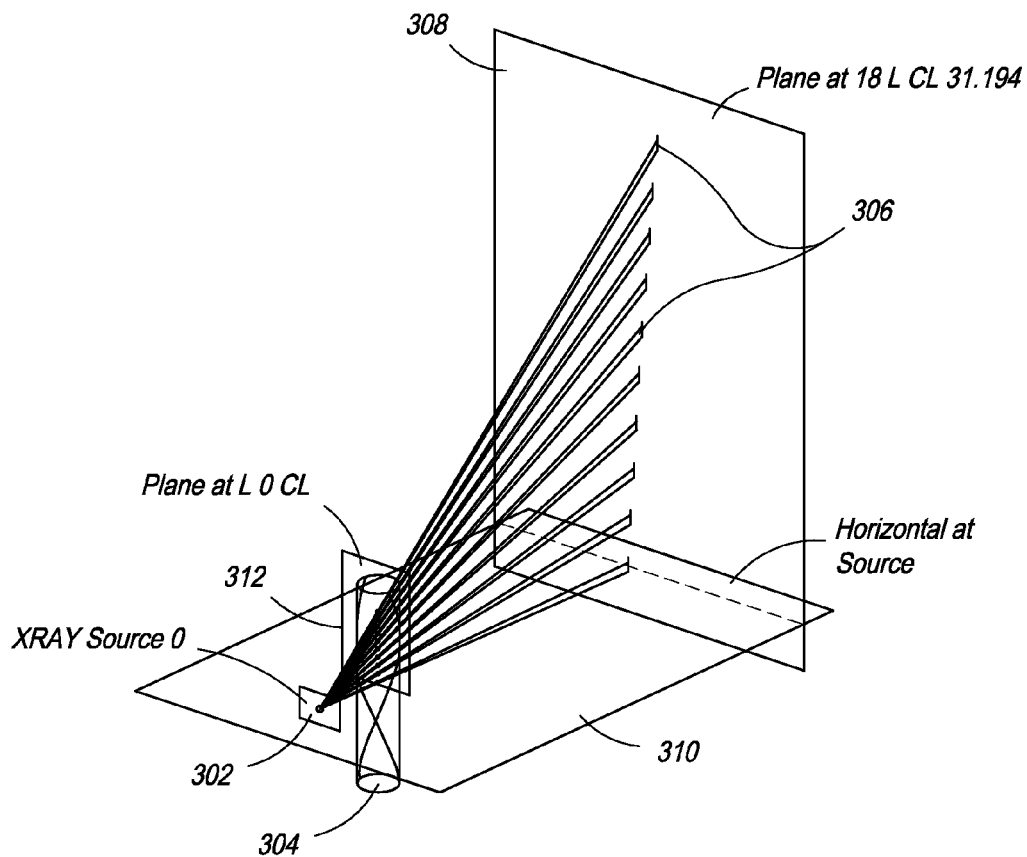


FIG. 3A

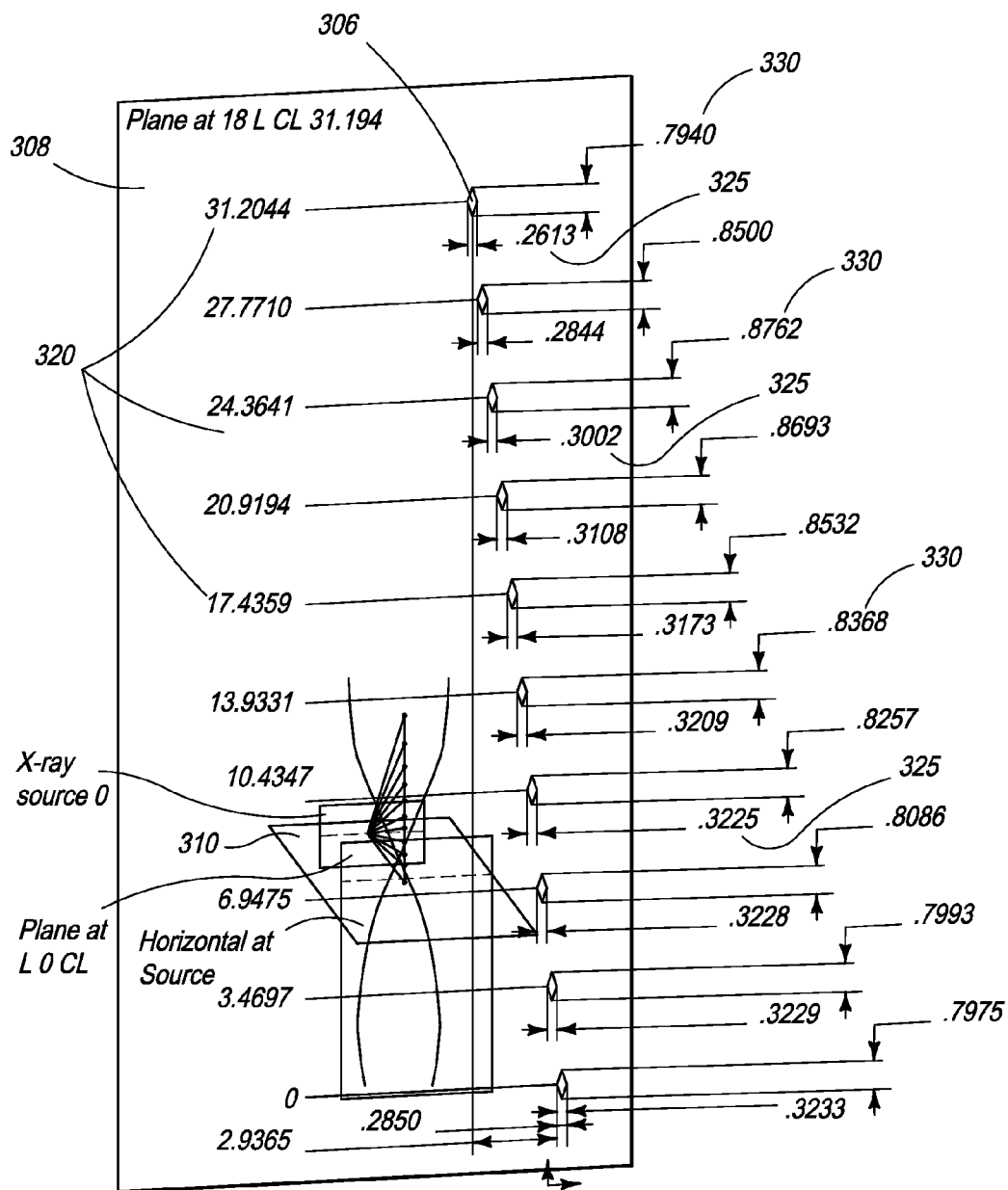


FIG. 3B

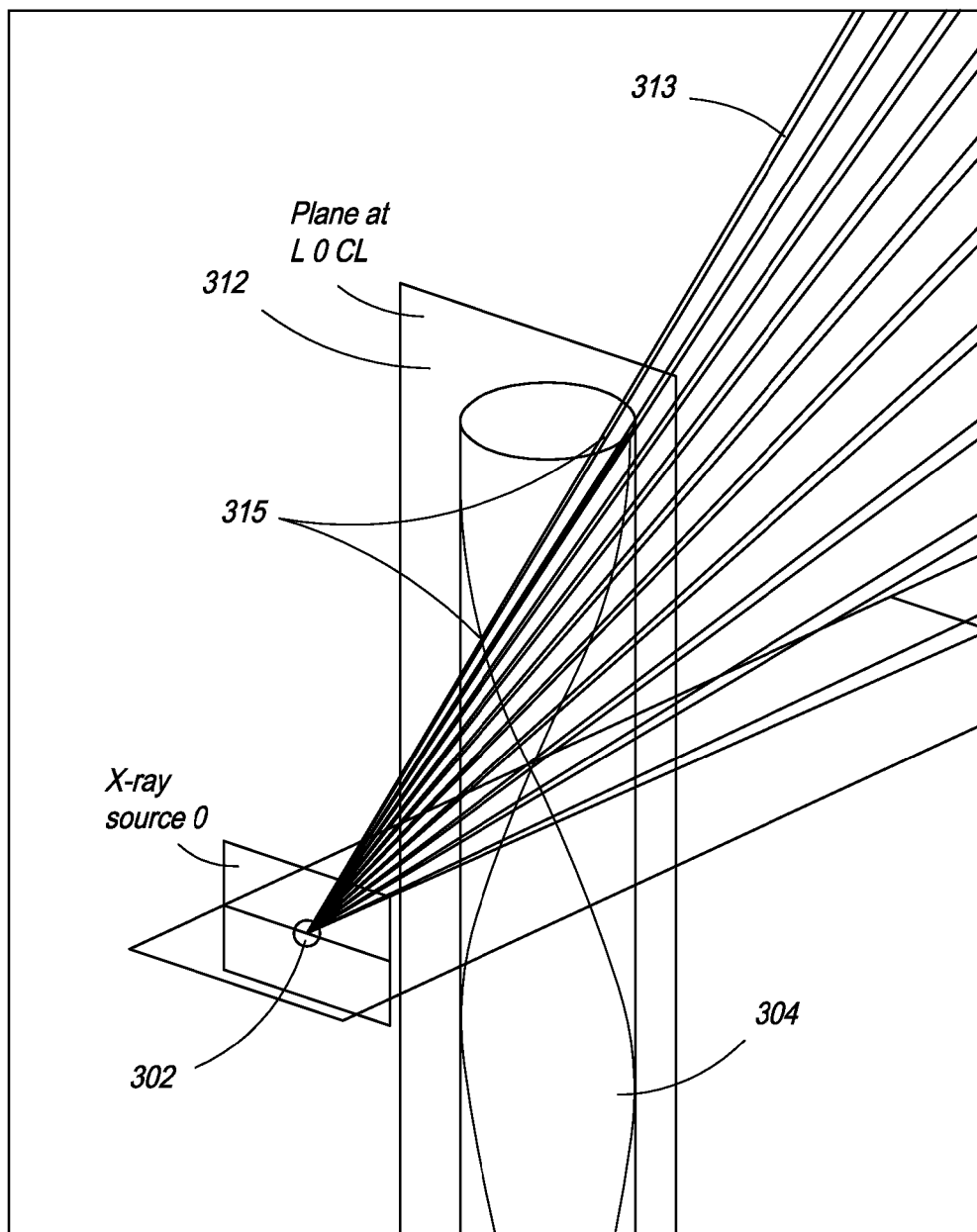
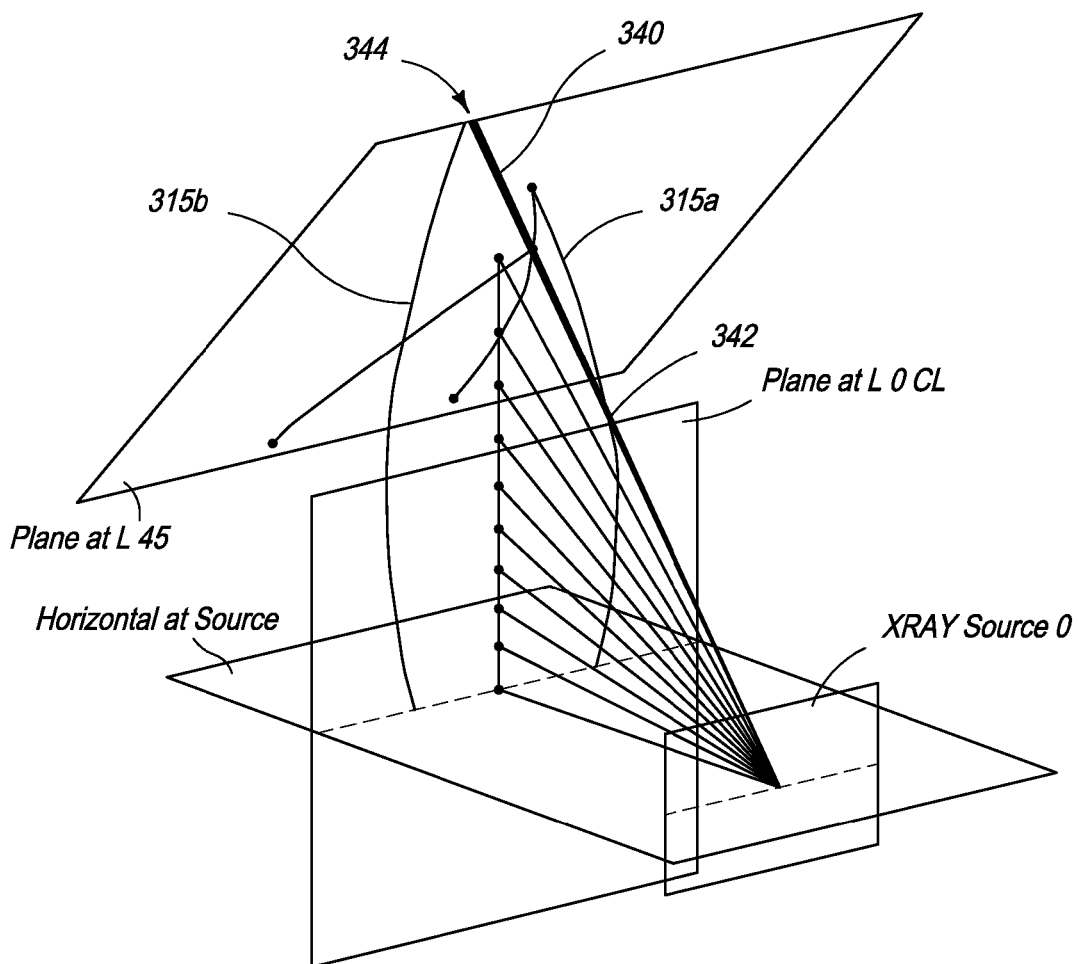
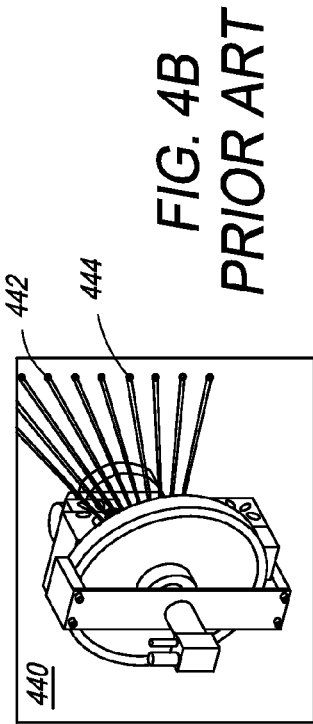


FIG. 3C



**FIG. 3D**



405 ANALYSIS OF CHOPPER WHEEL REV 2.0, 01-13-2009

410 ... To FIG. 4A-2

Angular Displacement	-45	-40	-35	-30	-25	-20	-15	-10	-5
Linear Displacement in Scan Plane	31.19421	26.17030	21.83506	18.00146	14.53742	11.34572	8.35166	5.49536	2.72638
Scan Displacement Between the Points	5.02391	4.33524	3.83360	3.46404	3.19170	2.99406	2.85630	2.76898	2.72638
Projected Target Width	0.45321	0.41861	0.39170	0.37068	0.35437	0.34192	0.33276	0.32651	0.32289
Projected Target Height	0.64496	0.54935	0.48028	0.42958	0.39214	0.36469	0.34508	0.33191	0.32430
Projected Target Size	0.29230	0.22996	0.18613	0.15924	0.13696	0.12469	0.11483	0.10837	0.10471

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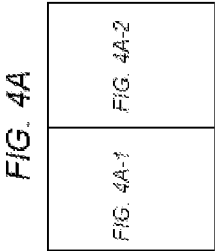


FIG. 4A-1  
PRIOR ART

From FIG. 4A-1 . . .

0	5	10	15	20	25	30	35	40	45
0.00000	2.72638	5.49536	8.35166	11.34572	14.53742	18.00146	21.83506	26.17030	31.19421
2.72638	2.72638	2.76898	2.85630	2.99406	3.19170	3.46404	3.83360	4.33524	5.02391
0.32108	0.32289	0.32651	0.33276	0.34192	0.35437	0.37068	0.39170	0.41861	0.45321
0.32178	0.32430	0.33191	0.34508	0.36469	0.39214	0.42958	0.48028	0.54935	0.64496
0.10332	0.10471	0.10837	0.11483	0.12469	0.13896	0.15924	0.18813	0.22996	0.29230

. . .

FIG. 4A-2  
PRIOR ART

FIG. 4C

FIG. 4C-1	FIG. 4C-2
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450 ANALYSIS OF SPINROLL

452 ... To FIG. 4C-2

SpinRoll Angular Rotation on Z Axis (Deg)	-90	-80	-70	-60	-50	-40	-30	-20	-10	
Beam Angular Displacement at 18" Scan Plane (Deg)	-45	-40	-35	-30	-25	-20	-15	-10	-5	
Linear Displacement at 18" Scan Plane (IN)	31.2044	27.7710	24.3641	20.9194	17.4359	13.9331	10.4347	6.9475	3.4697	
Scan Displacement Between the Points (IN)	3.4334	3.4069	3.4447	3.4835	3.5028	3.4984	3.4872	3.4778	3.4697	
Spot Size Width at the Spinroll CL (IN in X Axis)	0.0486	0.0539	0.0517	0.0556	0.0571	0.0582	0.0591	0.0597	0.0600	
Spot Size Height at the Spinroll CL (IN in Z Axis)	0.1045	0.1241	0.1154	0.1295	0.1343	0.1390	0.1437	0.1460	0.1477	
Spot Size at the Spinroll CL in IN"IN	0.0051	0.0067	0.0060	0.0072	0.0077	0.0081	0.0085	0.0087	0.0089	
Projected Target Width at SpinRoll L CL (IN in X Axis)	0.2613	0.2844	0.3002	0.3108	0.3173	0.3209	0.3225	0.3228	0.3229	
Projected Target Height at SpinRoll L CL (IN in Z Axis)	0.7940	0.8500	0.8762	0.8693	0.8532	0.8368	0.8257	0.8086	0.7993	
Projected Target Size in IN"IN at SpinRoll L CL	0.1037	0.1209	0.1315	0.1351	0.1354	0.1343	0.1331	0.1305	0.1290	

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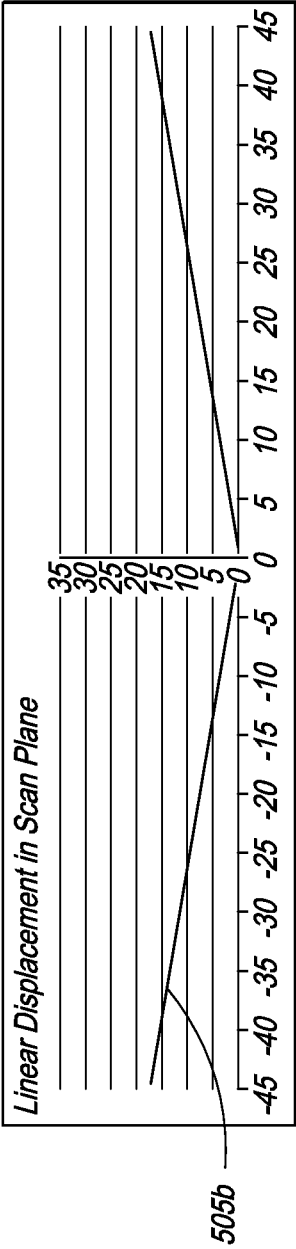
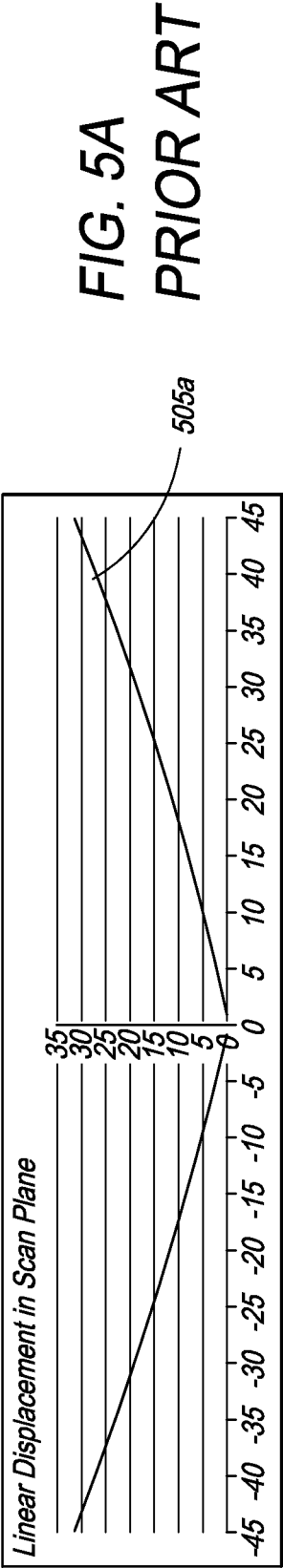
FIG. 4C-1

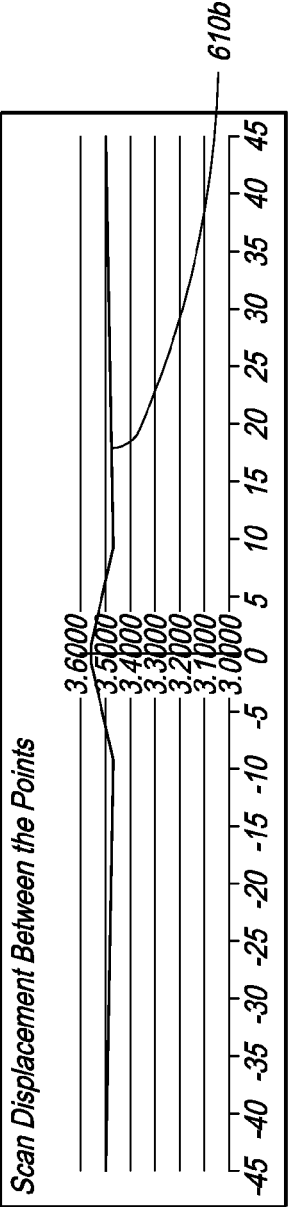
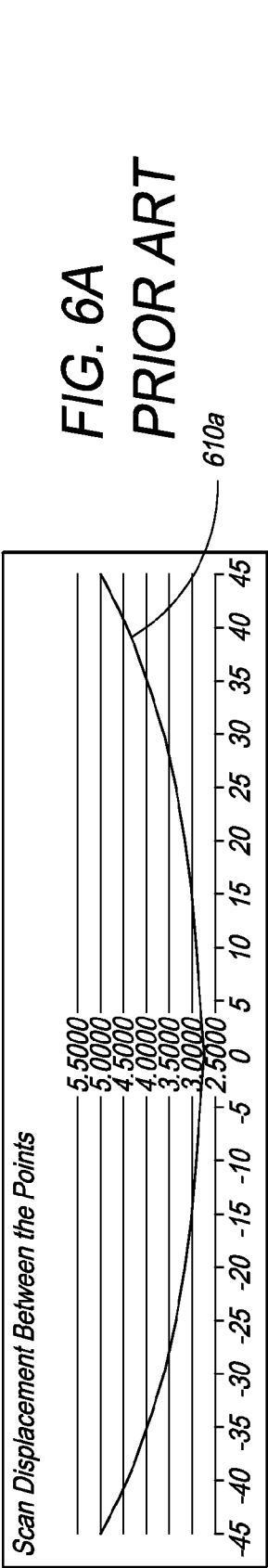
From FIG. 4C-1 . . .

0	10	20	30	40	50	60	70	80	90
0	5	10	15	20	25	30	35	40	45
0.000	3.4697	6.9475	10.4347	13.9331	17.4359	20.9194	24.3641	27.7710	31.2044
3.5489	3.4697	3.4778	3.4872	3.4984	3.5028	3.4835	3.4447	3.4069	3.4334
0.0602	0.0600	0.0597	0.0591	0.0582	0.0571	0.0556	0.0517	0.0539	0.0486
0.1485	0.1477	0.1460	0.1437	0.1390	0.1343	0.1295	0.1154	0.1241	0.1045
0.0089	0.0089	0.0087	0.0085	0.0081	0.0077	0.0072	0.0060	0.0067	0.0051
0.3233	0.3229	0.3228	0.3225	0.3209	0.3173	0.3108	0.3002	0.2844	0.2613
0.7975	0.7993	0.8086	0.8257	0.8368	0.8532	0.8693	0.8762	0.8500	0.7940
0.1289	0.1290	0.1305	0.1331	0.1343	0.1354	0.1351	0.1315	0.1209	0.1037

. . .

FIG. 4C-2





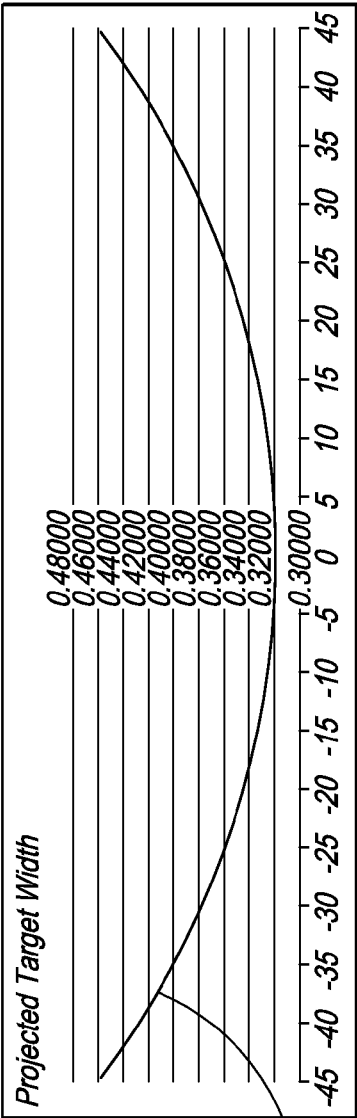


FIG. 7A  
PRIOR ART

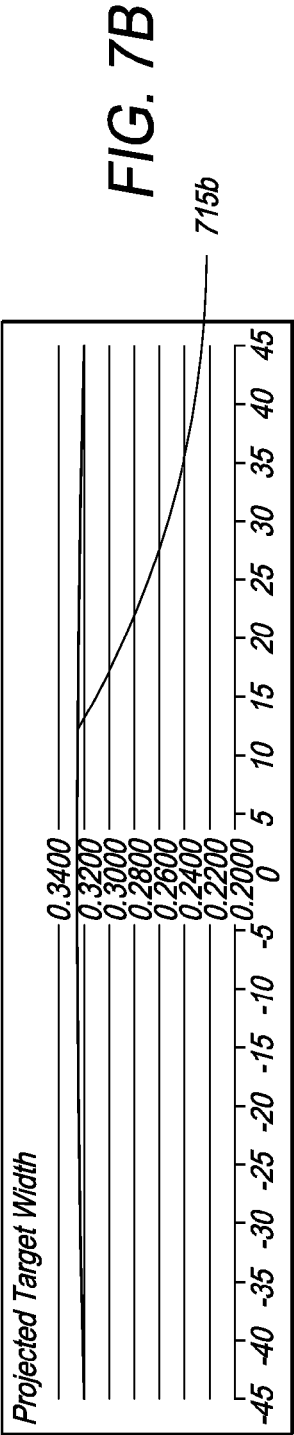
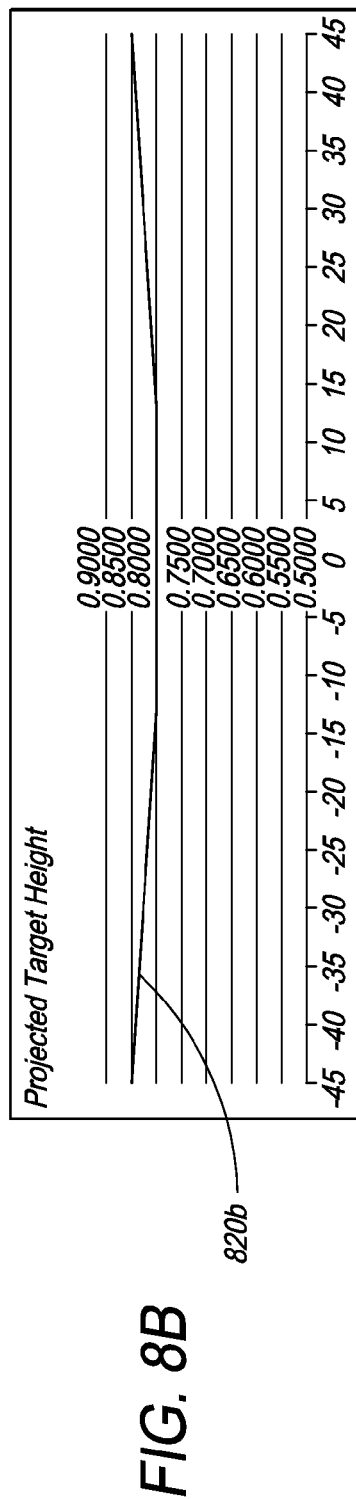
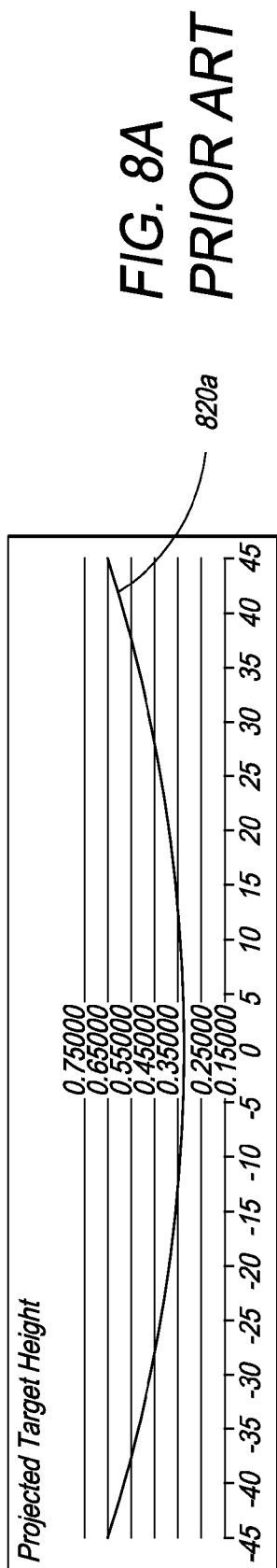


FIG. 7B





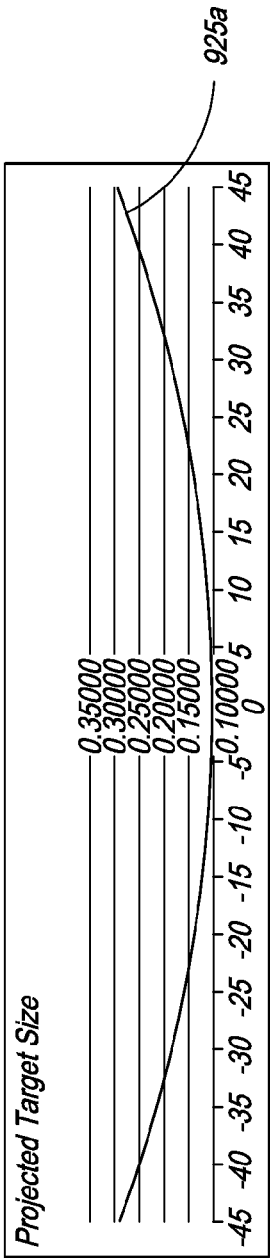


FIG. 9A  
PRIOR ART

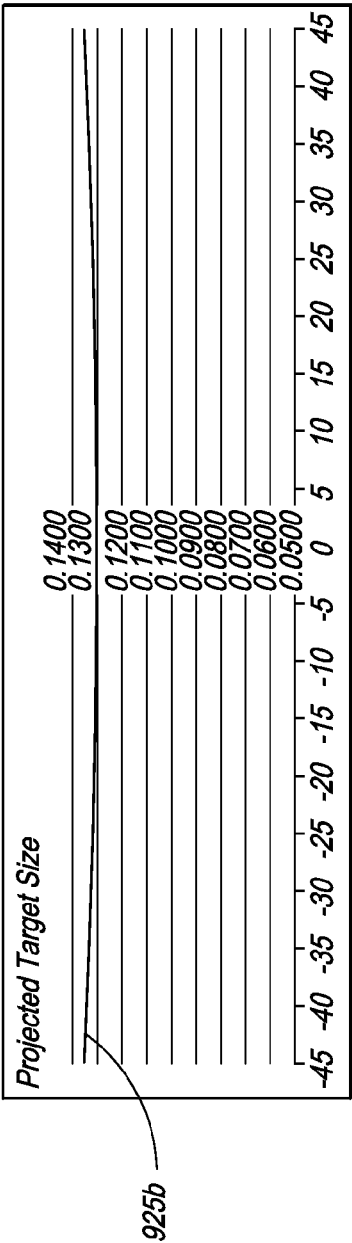


FIG. 9B

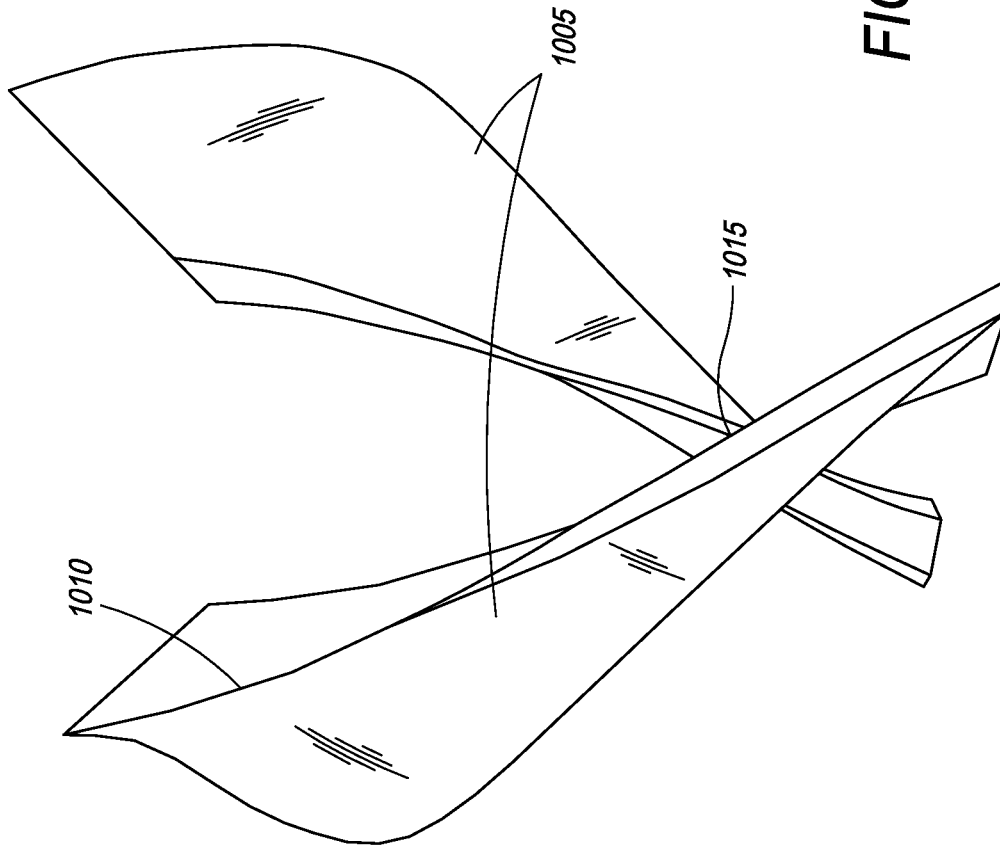
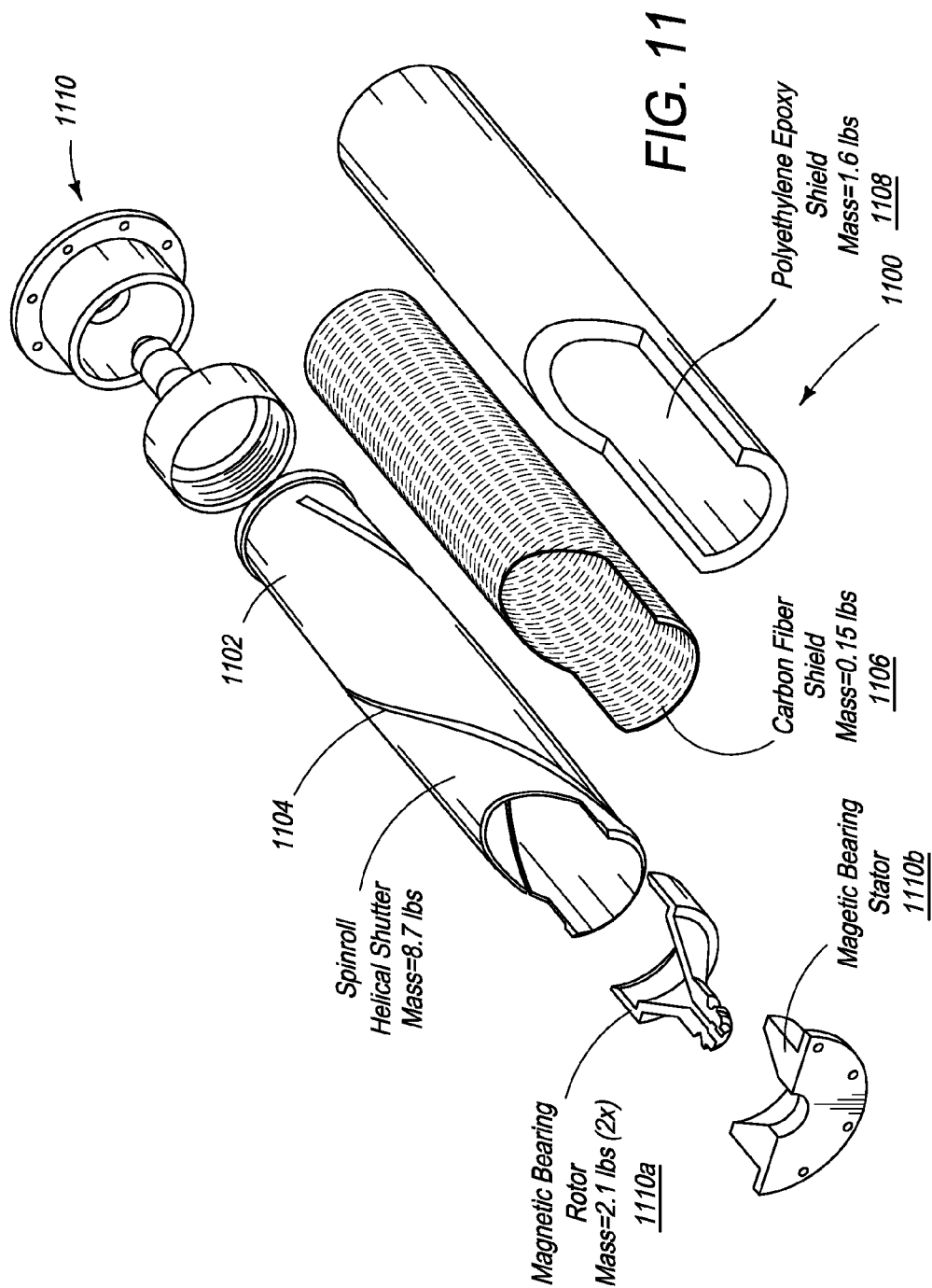
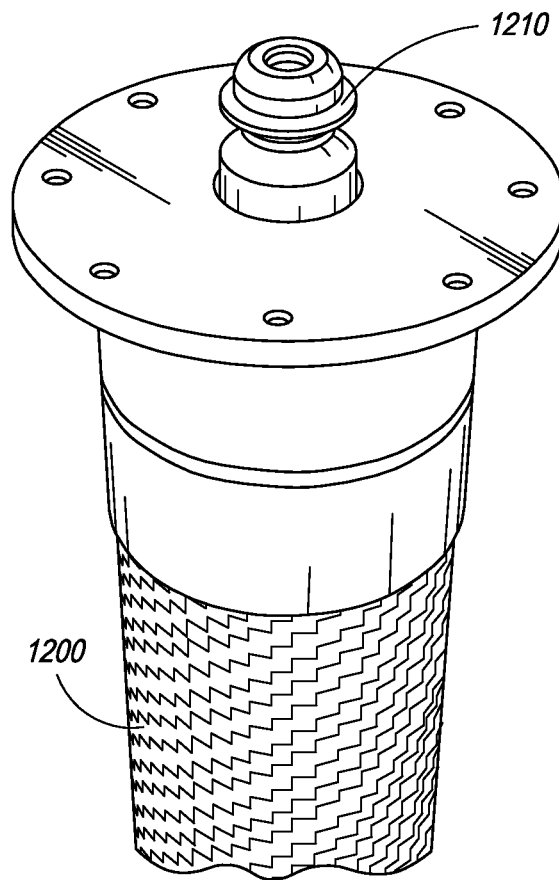


FIG. 10





**FIG. 12**

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**BEAM FORMING APPARATUS****CROSS-REFERENCE TO RELATED APPLICATIONS**

The present application is a continuation application of U.S. patent application Ser. No. 13/047,657, filed on Mar. 14, 2011 and entitled "Beam Forming Apparatus", which relies on U.S. Provisional Patent Application No. 61/313,772, filed on Mar. 14, 2010, for priority, both of which are herein incorporated by reference in their entirety.

**FIELD OF THE INVENTION**

The specification relates generally to security systems for screening threats contained on persons, and specifically, to a helical shutter for an electron beam system, and more specifically, to a system and method for modifying the shape of a travelling radiation scan beam, using helical apertures on a cylindrical surface.

**BACKGROUND OF THE INVENTION**

Security systems are presently limited in their ability to detect contraband, weapons, explosives, and other dangerous objects concealed under clothing. Metal detectors and chemical sniffers are commonly used for the detection of large metal objects and certain types of explosives; however, a wide range of dangerous objects exist that cannot be detected using these devices. Plastic and ceramic weapons increase the types of non-metallic objects that security personnel are required to detect. Manual searching of subjects is slow, is inconvenient, and would not be well tolerated by the general public, especially as a standard procedure in high traffic centers, such as airports.

It is known in the art that images of various types of material can be generated using X-ray scattering. The intensity of scattered X-rays is related to the atomic number ( $Z$ ) of the material scattering the X-rays. In general, for atomic numbers less than 25, the intensity of X-ray backscatter, or X-ray reflectance, decreases with increasing atomic number. Images are primarily modulated by variations in the atomic number of the subject's body. Low- $Z$  materials present a special problem in personnel inspection because of the difficulty in distinguishing the low- $Z$  object from the background of the subject's body which also has low- $Z$ .

Known prior art X-ray systems for detecting objects concealed on persons have limitations in their design and method that prohibit them from achieving low radiation doses, which is a health requirement, or prevent the generation of high image quality, which are prerequisites for commercial acceptance. An inspection system that operates at a low level of radiation exposure is limited in its precision by the small amount of radiation that can be directed against a person being searched. X-ray absorption and scattering further reduces the amount of X-rays available to form an image of the person and any concealed objects. In prior art systems this low number of detected X-rays has resulted in unacceptably poor image quality.

This problem is even more significant if an X-ray inspection system is being used in open venues such as stadiums, shopping malls, open-air exhibitions and fairs, etc. This is because that in such venues, people can be located both proximate to and/or at a distance from the machine. If a person being scanned is not very close to the X-ray machine, the obtained image may not be clear enough since the amount of radiation reaching the person is very low. This limits the range

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of scanning of the system to a few feet from the front of the machine. If, however, a person being scanned is too close to the X-ray machine, the amount of radiation impinging on the person may not be safe.

The amount of radiation exposure caused by known X-ray screening systems is commonly limited by the beam chopping apparatus employed in the systems.

Conventional beam chopping mechanisms generally consist of a disc wheel with collimator slits embedded therein at fixed distances from one another. The disc wheel is spun at a particular velocity and an X-ray beam of a particular energy is directed into more focused beams when passing through slits of the chopper wheel. The conventional chopper wheel is described in greater detail below throughout the specification in reference to the present disclosure.

It should be understood by persons having ordinary skill in the art that radiation sources are typically very heavy. In order to accommodate for the weight of the X-ray source, a chopper wheel configuration, as employed in the prior art, would need to be rather large. This substantially increases the weight of the system and makes it less portable. In addition, the chopper wheel, as employed in the prior art, is fraught with balance and gyroscopic effects. For example, the gyroscopic effect can be likened to a gyroscope toy where a string is pulled (such as a spinning top). As the top is spun fast, fluctuations in motion are not discernable, but, once it slows down, the top will start to wobble and vibrate. Thus, there is a certain RPM that must be kept to maintain balance. In addition, with increasing weight there are issues of humming noises at higher RPMs. In order to overcome the challenges in using conventional chopper wheel configurations, mechanical manipulation of the speed and size of the chopper wheel is necessary.

Therefore, what is needed is a beam chopping apparatus, and more specifically, a helical shutter for an electron beam system, that allows for variability in both velocity and beam spot size by modifying the physical characteristics or geometry of the beam chopper apparatus.

There is also need for a beam chopper apparatus, and more specifically, a helical shutter for an electron beam system, which provides a vertically moving beam spot with constant size and velocity to allow for equal illumination of the target.

Further, there is need for a beam chopping apparatus, and more specifically, a helical shutter for an electron beam system, which creates a wider field of view during operation.

Also, there is need for a beam chopping apparatus, and more specifically, a helical shutter for an electron beam system, that is lightweight and does not cause an X-ray source assembly employing the beam chopper to become heavy and difficult to deploy.

**SUMMARY OF THE INVENTION**

The present specification discloses an X-ray apparatus comprising: a) an X-ray source for emitting X-ray radiation; and b) a beam chopping (or beam forming) apparatus coupled to said X-ray source, wherein said beam chopping apparatus is adapted to receive said X-ray radiation and form a moving beam spot having a frequency, wherein said beam frequency is substantially constant.

Optionally, the beam chopping apparatus comprises a hollow cylinder having at least one helical aperture. The beam chopping apparatus comprises a hollow cylinder having at least two helical apertures. The beam has a linear scan velocity and wherein said linear scan velocity is varied by modifying a pitch and roll of at least one of said helical apertures. The beam has a linear scan velocity and wherein said linear

scan velocity is kept constant by modifying a pitch and roll of at least one of said helical apertures. The beam has a spot size and wherein said spot size is varied by modifying an aperture width of at least one of said helical apertures. The beam has a spot size and wherein said spot size is kept constant by modifying an aperture width of at least one of said helical apertures. The X-ray apparatus further comprises a motor for rotating said cylinder. The X-ray apparatus further comprises a controller for dynamically modifying a rotation speed of said cylinder to achieve a predetermined scan velocity. The rotation speed is equal to or less than 80,000 rpm. The beam has a scan velocity and a spot size and wherein scan velocity and spot size can be modified without varying a speed of said motor. The beam chopping apparatus comprises a hollow cylinder having at least two helical apertures, each having a length and an aperture width along said length and wherein said aperture width narrows along length. The beam chopping apparatus comprises a hollow cylinder having at least two helical apertures, each having a length and an aperture width along said length and wherein said aperture width increases along length.

In another embodiment, the X-ray apparatus comprises: a) an X-ray source for emitting X-ray radiation; and b) a beam chopping (or beam forming) apparatus coupled to said X-ray source, wherein said beam chopping apparatus is adapted to receive said X-ray radiation and form a moving beam spot having a velocity, wherein said beam velocity is substantially constant.

In another embodiment, the X-ray apparatus comprises: a) an X-ray source for emitting X-ray radiation; and b) a beam chopping (or beam forming) apparatus coupled to said X-ray source, wherein said beam chopping apparatus comprises a hollow cylinder with a first end and a second end defining a length of said cylinder and at least one helical aperture extending substantially along said length, wherein said cylinder is adapted to receive said X-ray radiation and emit said X-ray radiation through said helical aperture.

Optionally, the X-ray radiation passes through the helical aperture to produce a beam spot projection pattern, wherein said beam spot projection pattern comprises a beam spot moving vertically with a substantially constant velocity in a plane perpendicular to a plane of the X-ray source. The beam spot projection pattern comprises a beam spot moving vertically with a substantially constant velocity in a plane parallel to a plane of the beam chopping apparatus. The beam spot provides substantially equal illumination of a target object. The beam spot is trapezoidal. The helical aperture has a width that is more narrow at the second end relative to said first end.

#### BRIEF DESCRIPTION OF THE DRAWINGS

These and other features and advantages of the present invention will be appreciated, as they become better understood by reference to the following detailed description when considered in connection with the accompanying drawings, wherein:

FIG. 1 is a mechanical illustration of an exemplary design of one embodiment of the spin-roll chopper of the present invention;

FIG. 2 illustrates the spin-roll chopper mechanism of the present invention with an X-ray source and overlaid onto a conventional chopper wheel, showing the size difference between the two;

FIG. 3A illustrates a first view of the X-ray spot projection obtained by using an exemplary spin-roll chopper, in accordance with an embodiment of the present invention, illustrating empirical data at five degree increments of a total scan-

ning beam traversal of +45 degrees and spin-roll chopper rotation of -90 to +90 degrees;

FIG. 3B is a diagram showing the linear displacement values between flying spots and the relative shape and size of the flying spots that result from using the spin-roll chopper of the present invention, where the empirical data represents five degree increments of a total scanning beam traversal of 45 degrees and spin-roll chopper rotation of -90 to +90 degrees;

FIG. 3C illustrates a view of the X-ray beam projection at the center line of the vertical spin-roll chopper plane, showing the X-ray beam passing through two helical apertures when the X-ray beam traverses from the source at the 45 degree position;

FIG. 3D illustrates the X-ray beam projection at the center line of the vertical spin roll chopper plane as the radiation beam passes through the two helical slits of the spin-roll chopper, illustrating empirical data at five degree increments of a total scanning beam traversal of +45 degrees and spin-roll chopper rotation of -90 to +90 degrees;

FIG. 4A, comprising parts 4A-1 and 4A-2, is a table providing empirical data for a plurality of beam spot/target parameters obtained using a prior art disc wheel chopper, where data is provided at five degree increments of a total scanning beam traversal of -45 to +45 degrees;

FIG. 4B illustrates the resultant beam projection from using a prior art chopper wheel, showing that the width of the beam and size of the resultant spot vary across the scan;

FIG. 4C, comprising parts 4C-1 and 4C-2, is a table providing empirical data for a plurality of beam spot/target parameters obtained using the spin-roll chopper of the present invention, where data is provided at five degree increments of a total scanning beam traversal of -45 to +45 degrees and a spin-roll chopper rotation of -90 to +90 degrees;

FIG. 5A is a graphical illustration of the variation of the linear displacement of the beam spot, in the scan plane, using the prior art disc wheel chopper, where data is provided for a total scanning beam traversal of -45 to +45 degrees;

FIG. 5B is a graphical illustration of the variation of the linear displacement of the beam spot, in the scan plane, using the spin-roll chopper of the present invention, where data is provided for a total scanning beam traversal of -45 to +45 degrees and a spin-roll chopper rotation of -90 to +90 degrees;

FIG. 6A is a graphical illustration of the variation of scan displacement of the beam spot using the prior art disc wheel chopper, where data is provided for a total scanning beam traversal of -45 to +45 degrees;

FIG. 6B is a graphical illustration of the variation of scan displacement of the beam spot using the spin-roll chopper of the present invention, where data is provided for a total scanning beam traversal of -45 to +45 degrees and a spin-roll chopper rotation of -90 to +90 degrees;

FIG. 7A is a graphical illustration of the variation of projected target/beam spot width using the prior art disc wheel chopper, where data is provided for a total scanning beam traversal of -45 to +45 degrees;

FIG. 7B is a graphical illustration of the variation of projected target/beam spot width using the spin-roll chopper of the present invention, where data is provided for a total scanning beam traversal of -45 to +45 degrees and a spin-roll chopper rotation of -90 to +90 degrees;

FIG. 8A is a graphical illustration of the variation of projected target/beam spot height using the prior art disc wheel chopper, where data is provided for a total scanning beam traversal of -45 to +45 degrees;

FIG. 8B is a graphical illustration of the variation of projected target/beam spot height using the spin-roll chopper of

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the present invention, where data is provided for a total scanning beam traversal of  $-45$  to  $+45$  degrees and a spin-roll chopper rotation of  $-90$  to  $+90$  degrees;

FIG. 9A is a graphical illustration of the variation of projected target/beam spot size using the prior art disc wheel chopper, where data is provided for a total scanning beam traversal of  $-45$  to  $+45$  degrees;

FIG. 9B is a graphical illustration of the variation of projected target/beam spot size using the spin-roll chopper of the present invention, where data is provided for a total scanning beam traversal of  $-45$  to  $+45$  degrees and a spin-roll chopper rotation of  $-90$  to  $+90$  degrees;

FIG. 10 is a mathematical expression of the trajectory of the beam using the spin-roll chopper of the present invention with a single source, in accordance with one embodiment;

FIG. 11 illustrates a component design of the spin-roll chopper, in accordance with an embodiment of the present invention; and

FIG. 12 illustrates an assembled spin-roll chopper, equipped with a magnetic bearing assembly in accordance with an embodiment of the present invention.

#### DETAILED DESCRIPTION OF THE INVENTION

The present invention provides a spin-roll beam chopper apparatus, or a helical shutter for an electron beam system, which when implemented in a system for threat detection provides an improved method of screening individuals at security locations without exposing the individuals to high radiation while retaining the efficiency of the screening process. The beam chopper of the present invention allows for maximum threat detection performance and image clarity irrespective of the individual's distance from the screening system. In addition, the spin-roll chopper of the present invention is advantageous in that it can be spun at relatively high speeds, and therefore will effectively reduce the scan time required per person. Further, the spin-roll chopper of the present invention allows for variable velocity and beam spot size with modification of the physical characteristics or geometry of the spin-roll chopper.

In one embodiment of the present invention, the spin-roll chopper is used in conjunction with a threat detection system in which a radiographic image is formed using any available radiation imaging technique for "body imaging" such as, but not limited to X-ray scattering, infrared imaging, millimeter wave imaging, RF imaging, radar imaging, holographic imaging, CT imaging, and MRI. Any "body imaging" system that has the potential for displaying body detail may be employed. In one embodiment, any photodetectable radiation or any radiation source with a light beam may be employed with the spin-roll chopper of the present invention.

The following disclosure is provided in order to enable a person having ordinary skill in the art to practice the invention. Language used in this specification should not be interpreted as a general disavowal of any one specific embodiment or used to limit the claims beyond the meaning of the terms used therein. The general principles defined herein may be applied to other embodiments and applications without departing from the spirit and scope of the invention. Also, the terminology and phraseology used is for the purpose of describing exemplary embodiments and should not be considered limiting. Thus, the present invention is to be accorded the widest scope encompassing numerous alternatives, modifications and equivalents consistent with the principles and features disclosed. For purpose of clarity, details relating to technical material that is known in the technical fields related

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to the invention have not been described in detail so as not to unnecessarily obscure the present invention.

In various embodiments, the present invention provides a unique beam chopping mechanism that is designed to present a helical profile shutter (aperture), formed on a cylinder, for X-ray beam scanners. FIG. 1 illustrates an exemplary design for one embodiment of the spin-roll chopper, as used in various embodiments of the present invention. Beam chopper **102** is, in one embodiment, fabricated in the form of a hollow cylinder having helical chopper slits **104**. The cylindrical shape enables the beam chopper **102** to rotate about the Z-axis and along with the helical apertures **104**, create a spin-roll motion, which provides effective scanning and therefore good image resolution, as described below, while at the same time keeping the chopper lightweight and having less moment of inertia as the spin-roll mass is proximate to the axis of rotation. Stated differently, the radius of the spin-roll chopper is small compared to prior art beam chopping mechanisms, and in particular, the disc chopper.

In one embodiment, the hollow cylinder has a height **120** of 7.23 inches at the half-way point along its vertical axis. Therefore, in one embodiment, the full height of the cylinder is 14.46 inches. The helical slits **104**, in one embodiment, have a helical twist angle **125** of 112.5 degrees, a pitch of 23.1250 degrees and a roll of 0.3125 degrees. It should be noted that the helical twist angle **125** represents the angle of motion of the helical aperture from the y-axis (center line) when the cylinder is spun about the Z-axis a total of 90 degrees.

Thus, an X-ray beam scanner employing the spin-roll chopper of the present invention effectuates beam chopping by rotating the hollow cylinder **102** machined with at least two helical slits **104**, which enables X-ray beam scanning with both constant and variable linear scan beam velocity and scan beam spot size. The spin-roll chopper of the present invention enables both constant and variable linear scan beam velocity by manipulating the geometry of the helical apertures. In one embodiment, the velocity is varied or kept constant by manipulating the pitch and roll of the helical apertures along the length of the spin-roll chopper. Thus, it is possible to have a constant speed or to slow the scan down towards areas where more resolution is desired.

The spin-roll chopper of the present invention also enables variable and constant beam spot size by manipulating the geometry of the helical apertures, thus varying the resultant beam power. In one embodiment, it is possible to manipulate the actual width of the aperture to alter the beam spot size. In one embodiment, the width of the helical aperture varies along the length of the spin-roll chopper cylinder to compensate for the varying distance of the aperture from the center of the source and allow for uniform beam spot projection along the scan line. Thus, in one embodiment, the farther the aperture is away from the source, the narrower the width of the helical aperture to create a smaller beam spot size. In one embodiment, the closer the aperture is to the source, the wider the helical aperture to create a larger beam spot size. This structure is described in greater detail below.

When employed in a body scanning system, it is possible to vary the pitch and roll and width of the helical apertures such that more beam scanning power is directed towards areas of the body (hair, feet, etc) that require more detail and resolution and less power is directed towards areas of the body (midsection, etc.) that are more sensitive to radiation.

Helical slits **104** also ensure that the projection of the X-ray beam is not limited by the dual collimation of the two slits. As described in greater detail below, dual collimation refers to the concept whereby the X-ray beam will pass through two



helical slits at any given point in time. The resultant X-ray beam trajectory **130** is also shown in FIG. **1** and described in greater detail with respect to FIG. **10** below. In one embodiment, a pair of helices will produce one travelling beam. In another embodiment, additional pairs of helices may optionally be added to produce additional travelling beams depending upon scanning requirements. It should be noted that the chopper wheel of the prior art is only capable of producing one scanning beam.

In an embodiment of the present invention a plurality of viewing angles ranging from sixty degrees to ninety degrees can be obtained through the helical slits in the spin-roll chopper. In one embodiment, the scan angle is a function of the distance between the spin-roll chopper and both the source and the target. In addition, the overall height and diameter of the spin-roll chopper affects the viewing angle. The closer the spin-roll is placed to the source, the smaller the spin-roll chopper will need to be and similarly, the farther the spin-roll chopper is placed from the source, the larger the spin-roll chopper would need to be.

FIG. **2** illustrates a beam chopping mechanism using the spin-roll chopper described with respect to FIG. **1**. Referring to FIG. **2**, the cylindrical spin-roll chopper **202** is placed in front of a radiation source **204**, which, in one embodiment, comprises an X-ray tube. In one embodiment, rotation of the chopper **202** is facilitated by including a suitable motor **208**, such as an electromagnetic motor. In another embodiment, as described in greater detail below, magnetic bearings are employed to facilitate rotational movement of the spin-roll chopper of the present invention. The speed or RPM of rotation of the spin-roll chopper system is dynamically controlled to optimize the scan velocity. In one embodiment, the spin-roll chopper system is capable of achieving speeds up to 80K RPM.

In one embodiment, a radiation shield (not shown) is provided on radiation source **204** such that only a fan beam of radiation is produced from the source. The fan beam of radiation emits X-rays and then passes through the spin-roll chopper, which acts as an active shutter. Thus, there is only a small opening when the spin-roll chopper, and therefore helical apertures are rotating, which provides the moving flying spot beam.

FIG. **2** also shows a conventional, prior art disc chopper wheel **210** superimposed upon the source along with the spin-roll chopper. It can be seen from FIG. **2** that chopper wheel **210** is substantially larger than spin-roll chopper **202**.

For prior art chopper wheels, because of the round nature of the chopper wheel itself, the resultant flying spot beam has different acceleration and deceleration coming in right on the axis. Also, the chopper wheel itself has only one opening at each point that the ray passes through. Since the geometrical characteristics of the singular aperture cannot be changed, the farther the slit is from the center, the bigger the beam, and the closer the slit is from the center, the smaller the beam. Further, the velocity and spot size can only be mechanically manipulated using the prior art chopper wheel, by varying the speed of the motor attached to the chopper wheel. It should be noted, however, that since there are multiple apertures in the disc chopper wheel, there will always be a variance in the frequency and the scanning line because it is difficult to create each aperture such that they behaves in the exact same manner, as is known to those of skill in the art. The spin-roll chopper of the present invention overcomes these disadvantages because it is designed such that the frequency is continuous throughout.

FIGS. **3A** to **3D** illustrate a geometrical rendering of a flying X-ray spot beam projection obtained by using the spin-

roll chopper of the present invention, described in FIG. **1**, showing empirical data captured at five degree increments of a total scanning beam traversal of +45 degrees and spin-roll chopper rotation of -90 to +90 degrees. Thus, to generate empirical data, the scan is frozen in time at 5 degree increments of a total scanning beam traversal of 45 degrees. It should be understood, however, that the movement of the spin-roll and traversal of the scanning beam are continuous in application.

Referring to FIGS. **3A** through **3D** simultaneously, radiation emitted by a radiation source **302**, such as an X-ray source, is modulated by the spin-roll chopper **304**. The radiation beam, at each rotation, passes through two helical slits **315** of the chopper **304** to produce the resultant beam spot projection pattern (target) **306**, in the "target" plane **308** which, in one embodiment, is perpendicular to the plane **310** of the X-ray source and parallel to the plane **312** of the chopper **304**. In one embodiment, "target" plane **308** is located 18 inches from the source **302**. It should be noted herein that these scan points, while empirical data points, are representative of real motion of the beam and chopping mechanisms, and are presented to show the advantages of the present invention. Thus, it should be understood that the true movement of the traversing radiation beam and rotation of the spin-roll chopper are continuous.

FIG. **3B** is a diagram showing the linear displacement values between flying spots and the relative shape and size of the flying spots that result from using the spin-roll chopper of the present invention, where the empirical data represents five degree increments of a total scanning beam traversal of 45 degrees and spin-roll chopper rotation of -90 to +90 degrees. As shown more clearly in FIG. **3B**, in one embodiment, the beam spot pattern **306** produced exhibits characteristics consistent or superior to that of detection systems using prior art wheel chopping mechanisms. As mentioned above, the spin-roll chopper **304** allows for customization of the size and position of the beam spot **306** by modifying the helical aperture width and helical pitch and roll along the cylinder. FIG. **3B** illustrates exemplary values of the linear displacements **320**, at scan plane **308**, along with projected target widths **325** and projected target heights **330** for angular rotations of the cylinder varying from -90 to +90 degrees.

The resultant beam spot **306** is trapezoidal in shape, in one embodiment. The greater the height of the trapezoidal spot and the narrower the width of the trapezoidal spot, the higher the resolution. Since the flying spot beam travels vertically, having a height that is longer in the flying direction yields better scan performance. This is because in "aggregating" the flying beam spot projections, taller adjacent beam spots will be closer to one another and overlap, thus creating a continuous scan line at a higher energy, with better resolution, resulting in a higher resolution image. In addition, the smaller the resultant flying spot, the greater the power, because it is more focused.

FIG. **3C** illustrates a view of the X-ray beam projection at the center line of the vertical spin-roll chopper plane **312**, showing the X-ray beam **313** passing through two helical apertures **315** on spin-roll chopper **304** when the X-ray beam traverses from source **302** is at the 45 degree position.

FIG. **3D** illustrates the X-ray beam projection at the center line of the vertical spin roll chopper plane as the radiation beam passes through the two helical slits of the spin-roll chopper, illustrating empirical data at five degree increments of a total scanning beam traversal of +45 degrees and spin-roll chopper rotation of -90 to +90 degrees. As shown in FIG. **3D**, the beam **340** will pass through a first aperture point **342** on the spin-roll chopper helical aperture **315a** and then propa-

gate through a second aperture point **344** on the spin-roll chopper helical aperture **315b**.

The spin-roll chopper of the present invention provides a vertically moving beam spot with substantially constant velocity to allow for equal illumination of the target, unlike the prior art spinning disc chopper wheel. Thus, the spin roll chopper of the present invention moves and projects the beam spot substantially precisely and at a substantially constant speed. Also, the spin roll allows for the beam to be substantially equal in size at all points on the object. Thus, the radiation is a function of power and distance and using the spin roll the speed of the beam can be controlled precisely for even power distribution of the flying beam (such that power and distance are equal at all points). Again, using the spin roll chopper of the present invention attenuation to the shape of the scanning beam can be provided such that it will change the shape with the axis of the scanning beam itself. The distinctions between a conventional chopper wheel and the spin roll chopper of the present invention are described with respect to FIGS. **4A**, **4B**, **4C**, **5A**, **5B**, **6A**, **6B**, **7A**, **7B**, **8A**, **8B**, **9A**, and **9B**.

FIG. **4A** is a table providing empirical data for a plurality of beam spot/target parameters obtained using a prior art disc wheel chopper, where data is provided at five degree increments of a total scanning beam traversal of  $-45$  to  $+45$  degrees. FIG. **4A**, comprising parts **4A-1** and **4A-2**, shows variations of a plurality of parameters for various angular displacements **405** of the source and thus, beam, such as but not limited to linear displacement **410** in the scan plane (representing a slice somewhere along the length of the distance from source to target); scan displacement **415** between points (where the points are flying spots arbitrarily chosen to provide empirical data); projected width **420**; projected target height **425**; and projected target size **430**, all of which are described in greater detail below.

FIG. **4B** illustrates the resultant beam projection from using a prior art chopper wheel **440**, showing that the width of the beam **442** and size of the resultant spot **444** vary across the scan. Persons of ordinary skill in the art would appreciate that a conventional chopper wheel comprises four slits, each one at  $90$  degrees from the other on the periphery of the flange. It is not realistic, however, to assume that these slits will be manufactured and cut at exactly  $90$  degrees. Thus, when the chopper wheel is rotated, not only is there a skew due to the inexact nature of these slits, but a skew due to the beam size depending on the distance of the slit and thus beam from the center of the chopper wheel as described above. In addition, on the prior art chopper wheel, the size of the slit cannot be easily manipulated as there is only one opening at each point and not a continuous slit. This results in the flying spot to be at distinct and uneven distances from each point on the chopper wheel.

FIG. **4C** is a table providing empirical data for a plurality of beam spot/target parameters obtained using the spin-roll chopper of the present invention, where data is provided at five degree increments of a total scanning beam traversal of  $-45$  to  $+45$  degrees and a spin-roll chopper rotation of  $-90$  to  $+90$  degrees. Thus, FIG. **4C**, comprising parts **4C-1** and **4C-2**, shows variations of a plurality of parameters for various angular rotations **450** of the spin-roll chopper of the present invention and various angular displacements **452** of the source and thus, resultant beam, such as, but not limited to linear displacement **454** in the scan plane (representing a slice somewhere along the length of the distance from source to target, and in this case  $18$  inches); scan displacement **456** between points (where the points are flying spots arbitrarily chosen to provide empirical data); spot size width **458** at the vertical

plane located at the center line of the spin-roll chopper and along the z-axis; spot size height **460** at the vertical plane located at the center line of the spin-roll chopper and along the z-axis; spot size area **462** (in square inches) at the vertical plane of the center line of the spin-roll chopper and along the z-axis; projected target width **464** across the x-axis vertical plane of the center line of the spin-roll chopper and along the z-axis; projected target height **466** along the z-axis at the vertical plane of the center line of the spin-roll chopper and along the z-axis; and projected target size **468**, vertical plane of the center line of the spin-roll chopper and along the z-axis, all of which are described in greater detail below.

FIG. **5A** is a graphical illustration of the variation of the linear displacement of the beam spot, in the scan plane, using the prior art disc wheel chopper, where data is provided for a total scanning beam traversal of  $-45$  to  $+45$  degrees. It has been found that these spots track in patterns of four, representing the four slits in the wheel. FIG. **5A** shows a graph wherein the beam spots have variable linear displacement **505a** of spots in the scan plane for the chopper wheel as compared to linear displacement **505b** for the spin-roll chopper shown in FIG. **5B**. FIG. **5B** is a graphical illustration of the variation of the linear displacement of the beam spot, in the scan plane, using the spin-roll chopper of the present invention, where data is provided for a total scanning beam traversal of  $-45$  to  $+45$  degrees and a spin-roll chopper rotation of  $-90$  to  $+90$  degrees. The resolution depends on how the chopper wheel is spun and at what velocity, as described in detail above. The faster the chopping mechanism is spun, the smaller the variance in frequency. The spin-roll chopper of the present invention can be spun at RPMs up to  $80K$ .

FIG. **6A** is a graphical illustration of the variation of scan displacement of the beam spot using the prior art disc wheel chopper, where data is provided for a total scanning beam traversal of  $-45$  to  $+45$  degrees, showing that the scan displacement **610a** between points is skewed for the chopper wheel.

FIG. **6B** is a graphical illustration of the variation of scan displacement of the beam spot using the spin-roll chopper of the present invention, where data is provided for a total scanning beam traversal of  $-45$  to  $+45$  degrees and a spin-roll chopper rotation of  $-90$  to  $+90$  degrees, showing, however, that the scan displacement **610b** is substantially straight for the spin roll chopper as shown in FIG. **6B**. This is because in the spin-roll chopper of the present invention there are two helical slits that overlap at every  $180$  degrees. Thus, the radiation beam has two slits to run through such that at one point in time, the X-rays will pass through both slits to create the beam spot. This is referred to as dual collimation and also prevents frequency deviation thereby keeping the frequency substantially constant. Since the slits in the spin roll are continuous, there is less error in the "distance between slits", while with the chopper wheel it is, in practice, quite difficult to get the slits at exactly  $90$  degrees from one another.

In accordance with an embodiment of the present invention, at certain distances from the center of the beam, the helical slit (of the spin roll chopper) is kept wider than others. FIG. **10** shows a mathematical expression of the trajectory **1005** of the beam using a single source, in accordance with one embodiment. In order to get the dimensions of the helical cuts in the spin-roll cylinder, one dimension of this trajectory was removed. More specifically, the slit is narrower at the top **1010** because there is a greater distance for the beam to travel. Note that when an X-ray beam travels through any opening, the beam is collimated. The farther the beam travels, the wider the resultant "spot" (fan beam) is at the end of the beam. By making the slit narrower at the top **1010**, this greater distance

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and beam widening is accounted for. In addition, the slit is made wider where the distance to the object is shorter, such as at point **1015**. Also, persons of ordinary skill in the art should appreciate that by controlling the size of the slit one can control the density of the beam that is projected straight through.

FIG. 7A shows a graphical illustration of the variation of projected target/beam spot width using the prior art disc wheel chopper, where data is provided for a total scanning beam traversal of  $-45$  to  $+45$  degrees, while FIG. 7B is a graphical illustration of the variation of projected target/beam spot width using the spin-roll chopper of the present invention, where data is provided for a total scanning beam traversal of  $-45$  to  $+45$  degrees and a spin-roll chopper rotation of  $-90$  to  $+90$  degrees. FIG. 7B shows that, for the spin-roll, there is equal resultant beam/spot width **715b** throughout, because the slit is wider at shorter distances from the object (under inspection) and narrower at longer distances from the object to compensate for this distance ( $-90$  degrees to  $+90$  degrees)—as compared to the relatively varying beam/spot width **715a** for the chopper wheel as shown in FIG. 7A.

FIG. 8A is a graphical illustration of the variation of the projected target/beam spot height using the prior art disc wheel chopper, where data is provided for a total scanning beam traversal of  $-45$  to  $+45$  degrees, while FIG. 8B is a graphical illustration of the variation of projected target/beam spot height using the spin-roll chopper of the present invention, where data is provided for a total scanning beam traversal of  $-45$  to  $+45$  degrees and a spin-roll chopper rotation of  $-90$  to  $+90$  degrees. Thus, FIG. 8A shows that for the chopper wheel the projected target height **820a** varies significantly when compared to the projected target height **820b**, in FIG. 8B, for the spin-roll.

FIG. 9A is a graphical illustration of the variation of projected target/beam spot size using the prior art disc wheel chopper, where data is provided for a total scanning beam traversal of  $-45$  to  $+45$  degrees, while FIG. 9B is a graphical illustration of the variation of projected target/beam spot size using the spin-roll chopper of the present invention, where data is provided for a total scanning beam traversal of  $-45$  to  $+45$  degrees and a spin-roll chopper rotation of  $-90$  to  $+90$  degrees. Again, as shown in FIG. 9A the projected target size **925a** for the chopper wheel varies significantly as compared to the projected target size **925b** of the spin-roll as shown in FIG. 9B.

FIG. 11 illustrates the design and fabrication of the spin-roll chopper, in accordance with an embodiment of the present invention. As illustrated, a hollow tungsten cylinder **1102** machined with helical slits **1104** forms the inner layer of spin-roll chopper assembly **1100**. The cylinder **1102** is formed from one or two pieces of tungsten formed together. Since tungsten is opaque to ionizing radiation, an X-ray beam will not pass through it. A carbon fiber fabric **1106** (such as, but not limited to Kevlar) is wrapped around the tungsten cylinder **1102**. The carbon fiber is transparent to the X-ray beams and thus, creates a window (moving aperture) through which the beam passes in the shape of the helical slits cut out of the tungsten cylinder **1102**.

Further, in one embodiment, an epoxy shield **1108**, such as a polyethylene epoxy shield is used to bind the carbon fiber **1106** to the tungsten cylinder **1102**. The epoxy shield also creates a window (moving aperture) through which the beams pass in the shape of the helical slits cut out of the tungsten. The epoxy shield prevents unraveling of the carbon fiber cover.

In a first embodiment, the cylinder is machine spun and fabricated from brass.

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In one embodiment, in order to form the epoxy shield around the carbon fiber coated tungsten cylinder, a chemical setting technique is employed whereby at least two liquid components are mixed together and upon mixing, the chemical components form a solid epoxy coating. In one embodiment, the solid epoxy coating formed is a polyethylene epoxy.

In one embodiment, in order to form the epoxy shield around the carbon fiber coated tungsten cylinder, a thermal setting technique is employed whereby the cylinder is placed into a spinning and heated epoxy powder mold (at say,  $400$  degrees C.) which is heated to the melting point to create a light structure with tungsten and Kevlar inside. In one embodiment, the epoxy shield **1108** has sufficient hardness, strength, and durability to withstand centrifugal forces of up to  $80\text{K RPM}$ .

In one embodiment, the spin roll chopper assembly **1100** is dynamically controlled for rotation using an electromagnetic motor drive.

In one embodiment, the light-weight chopper assembly **1100** is spun using a magnetic bearing assembly **1110**, which eliminates the need for a motor to spin the chopper, thereby contributing to keeping the chopper assembly further light-weight. The magnetic bearing assembly **1110** comprises a magnetic rotor **1110a**, and a magnetic bearing stator **1110b**. Besides a spinning motion, the magnetic bearing assembly **1110** is also used to provide magnetic levitation for the chopper during power-up (ON state) and power-down (OFF state), as well as during accidental power-failure.

Depending upon the material of the cylinder **1102** and the bearings used to support the rolling movement of the chopper, various ranges of RPMs are achievable. For example, a bare cylinder **1102** fabricated from brass with diamond bearings can be spun to achieve up to  $1\text{K RPMs}$ ; a bare cylinder **1102** fabricated from tungsten with diamond bearings can achieve up to  $4\text{K RPM}$ ; while a bare cylinder **1102** fabricated from tungsten and coated with Kevlar and epoxy and spun using diamond bearings can achieve up to  $80\text{K RPM}$ .

FIG. 12 illustrates the assembled spin roll chopper cylinder **1200**, along with the magnetic bearing assembly **1210**.

Persons of ordinary skill in the art would appreciate that magnetic bearings support the rolling motion of the spin-roll chopper without physical contact and permit relative motion with very low friction and no mechanical wear. In one embodiment, referring back to FIG. 11, the space between the rotor **1110a** and the stator **1110b** is filled with an inert gas, such as Argon, to suspend the spin roll in space and enable higher RPMs.

A magnetic bearing works on the principle of electromagnetic suspension and in one embodiment comprises an electromagnet assembly, a set of power amplifiers which supply current to the electromagnets, a controller, and gap sensors with associated electronics to provide the feedback required to control the position of the rotor within the gap. The power amplifiers supply equal bias current to two pairs of electromagnets on opposite sides of a rotor. This constant tug-of-war is mediated by the controller which offsets the bias current by equal but opposite perturbations of current as the rotor deviates by a small amount from its center position. The gap sensors are usually inductive in nature and sense in a differential mode. The power amplifiers in one embodiment are solid state devices which operate in a pulse width modulation (PWM) configuration. The controller is a microprocessor or DSP.

It should be appreciated that since the spin-roll chopper of the present invention can be spun very fast, it is possible to use the chopper with multiple X-ray beams. In one embodiment,

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four beams are used, with four separate corresponding detector panels to determine which beam is active.

The present invention provides that the distance of the spin-roll chopper is directly correlated with a minimum scan height. This allows for longer distance from source to the target, thereby extending the depth of field with respect to dose rate. Therefore, for a given depth of imaging, a smaller radiation dose is required in a threat detection system employing the spin-roll chopper of the present invention, as compared to other systems known in the art. In one embodiment, due to the kinematics and resultant moment of inertia of the spin-roll chopper of the present invention, it is insensitive to orientation.

In an exemplary embodiment, the spin-roll chopper is employed in a detection system which is implemented as a walk-through detection system. The novel design of the spin-roll chopper enables utilization of low-level radiation doses to detect weapons and dangerous materials, regardless of whether they consist of metal or low Z materials. Besides being employed for screening of passengers at airports and railway stations, at open and crowded venues such as stadiums and shopping malls, applications of the spin-roll chopper of present invention may be extended detection systems for inspecting the contents of vehicles and containers at transit points such as ports, border crossings and customs checkpoints, and other secure locations.

The above examples are merely illustrative of the many applications of the system of present invention. Although only a few embodiments of the present invention have been described herein, it should be understood that the present invention might be embodied in many other specific forms without departing from the spirit or scope of the invention. Therefore, the present examples and embodiments are to be considered as illustrative and not restrictive.

What is claimed is:

1. An X-ray apparatus comprising:  
an X-ray source for emitting X-ray radiation; and  
a beam chopping apparatus coupled to said X-ray source, wherein said beam chopping apparatus is adapted to rotate, receive said X-ray radiation and form a moving beam spot having a variance in frequency, wherein said variance in frequency decreases as said beam chopping apparatus is rotated faster.
2. The X-ray apparatus of claim 1 wherein said beam chopping apparatus comprises a hollow cylinder having at least one helical aperture.
3. The X-ray apparatus of claim 1 wherein said beam chopping apparatus comprises a hollow cylinder having at least two helical apertures.
4. The X-ray apparatus of claim 3 wherein said beam has a linear scan velocity and wherein said linear scan velocity is varied by modifying a pitch and roll of at least one of said helical apertures.
5. The X-ray apparatus of claim 3 wherein said beam has a linear scan velocity and wherein said linear scan velocity is kept constant by modifying a pitch and roll of at least one of said helical apertures.

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6. The X-ray apparatus of claim 3 wherein said beam has a spot size and wherein said spot size is varied by modifying an aperture width of at least one of said helical apertures.

7. The X-ray apparatus of claim 3 wherein said beam has a spot size and wherein said spot size is kept constant by modifying an aperture width of at least one of said helical apertures.

8. The X-ray apparatus of claim 2 further comprising a motor for rotating said cylinder.

9. The X-ray apparatus of claim 8 further comprising a controller for dynamically modifying a rotation speed of said cylinder to achieve a predetermined scan velocity.

10. The X-ray apparatus of claim 9 wherein said rotation speed is equal to or less than 80,000 rpm.

11. The X-ray apparatus of claim 8 wherein said beam has a scan velocity and a spot size and wherein scan velocity and spot size can be modified without varying a speed of said motor.

12. The X-ray apparatus of claim 1 wherein said beam chopping apparatus comprises a hollow cylinder having at least two helical apertures, each having a length and an aperture width along said length and wherein said aperture width narrows along length.

13. The X-ray apparatus of claim 1 wherein said beam chopping apparatus comprises a hollow cylinder having at least two helical apertures, each having a length and an aperture width along said length and wherein said aperture width increases along length.

14. An X-ray apparatus comprising:

an X-ray source for emitting X-ray radiation; and

a beam chopping apparatus coupled to said X-ray source, wherein said beam chopping apparatus rotates and comprises a hollow cylinder with a first end and a second end defining a length of said cylinder and at least one helical aperture extending substantially along said length, wherein said cylinder is adapted to receive said X-ray radiation and emit said X-ray radiation, having a variance in frequency, through said helical aperture and wherein said variance in frequency decreases as said beam chopping apparatus is rotated faster.

15. The X-ray apparatus of claim 14 wherein said X-ray radiation passes through the helical aperture to produce a beam spot projection pattern, wherein said beam spot projection pattern comprises a beam spot moving vertically with a substantially constant velocity in a plane perpendicular to a plane of the X-ray source.

16. The X-ray apparatus of claim 15 wherein said beam spot projection pattern comprises a beam spot moving vertically with a substantially constant velocity in a plane parallel to a plane of the beam chopping apparatus.

17. The X-ray apparatus of claim 16 wherein said beam spot provides substantially equal illumination of a target object.

18. The X-ray apparatus of claim 14 wherein said beam spot is trapezoidal.

19. The X-ray apparatus of claim 14 wherein said helical aperture has a width that is more narrow at the second end relative to said first end.

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